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RESEARCH ARTICLES

**Bernard Baumberger · Brice Isableu ·
Michelangelo Flückiger**

The visual control of stability in children and adults: postural readjustments in a ground optical flow

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Abstract The aim of this research was to analyse the development of postural reactions to approaching (AOF) and receding (ROF) ground rectilinear optical flows. Optical flows were shaped by a pattern of circular spots of light projected on the ground surface by a texture flow generator. The geometrical structure of the projected scenes corresponded to the spatial organisation of visual flows encountered in open outdoor settings. Postural readjustments of 56 children, ranging from 7 to 11 years old, and 12 adults were recorded by the changes of the centre of foot pressure (CoP) on a force platform during 44-s exposures to the moving texture. Before and after the optical flows exposure, a 24-s motionless texture served as a reference condition. Effect of ground rectilinear optical flows on postural control development was assessed by analysing sway latencies (SL), stability performances and postural orientation. The main results that emerge from this experiment show that postural responses are directionally specific to optical flow pattern and that they vary as a function of the motion onset and offset. Results showed that greater developmental changes in postural control occurred in an AOF (both at the onset and offset of the optical flow) than in an ROF. Onset of an approaching flow induced postural instability, canonical shifts in postural orientation and long latencies in children which were stronger than in the receding flow. This pattern of responses evolved with age towards an improvement in stability performances and shorter SL. The backward decreasing shift of the CoP in children evolved in adults towards forward postural tilt, i.e. in the opposite direction of the texture's motion. Offset of an AOF motion induced very short SL in children (which became longer in adult subjects), strong postural instability, but weaker shift of orientation compared to the receding one. Postural stability improved and orientation shift evolved to forward inclinations with age. SL remained almost constant across age at both onset and offset of the receding flow. Critical developmental periods seem to occur by the age of 8 and 10 years, as suggested by the transient 'neglect' of the children to optical flows. Linear vection was felt by 90% of the 7 year olds and decreased with age to reach 55% in adult subjects. The mature sensorimotor coordination subserving the postural organisation shown in adult subjects is an example aiming at reducing the postural effects induced by optical flows. The data are discussed in relation to the perceptual importance of mobile visual references on a ground support.

Keywords Posture adjustment · Balance · Stability · Ground optical flow · Child development · Human

B. Baumberger (✉) · M. Flückiger
Experimental Psychology Laboratory of Perception, FPSE, University of Geneva,
40 bd. du Pont d'Arve,
1205 Genève 4, Switzerland
e-mail: Bernard.Baumberger@pse.unige.ch
Tel.: +41-22-3799137
Fax: +41-22-3799229

B. Isableu
Centre de Recherches en Sciences du Sport, Université Paris-Sud XI,
Bâtiment 335,
91405 Orsay cedex, France

Introduction

The postural control system receives information about the body and its environment from three sensory systems: visual, vestibular and somatosensory. Of the three sensory inputs, the visual system is the one that has received the most attention, especially regarding postural control development in infants and children. Indeed, stability is highly dependent on the visual system (Edwards 1946) in human beings. One of the most efficient ways of showing how we perceive the movement of visual surroundings is to record postural reactions of standing subjects. Generally, the mobile stimuli used in such research attempt to simulate the characteristics of an optical flow produced by a moving observer during locomotion (Gibson 1950). Thus, since the classic experiments of Witkin and Wapner (1950) later extended by Lishman and Lee (1973), Lee and

Aronson (1974), Lee and Lishman (1975) and Lestienne et al. (1976, 1977), systematic and global postural readjustments have been observed when the optical environment is moved by means of different devices. Intriguingly, these compensatory responses appear despite the fact that both vestibular and motosomatosensory inputs still indicate reliable information about verticality for controlling both postural orientation and stability.

Effect of optical flow on standing balance in adult

An important variable for the postural control concerns the structure of the visual flow (lamellar or radial) as related to its retinal projection. Historically, the lower sensitivity of the central retina to motion perception has been recognised as the main factor to explain enhanced vection effects with a peripheral stimulation (Johansson 1977; Andersen and Braunstein 1985). The functional predominance of this factor has been contrasted with the results of experiments using linear instead of circular motion patterns (Brandt et al. 1976). Thus Stoffregen (1985, 1986) has shown that it is mainly the opposition between lamellar and radial flows that determines the principal difference in motion perception. Andersen and Dyre (1989) suggested that both radial and lamellar optical flows are effective for determining spatial orientation when stimulation is limited to the central visual field. However, some of these conclusions still remain controversial. Contrary to previous findings, radial flow in peripheral vision was found to produce significant coherent body sways (Frigon 1996). Consistent with this outcome, Bardy et al.'s (1996) findings supported a control principle subserving the visual regulation of posture, which would be based on the structure of the optical flow pattern, regardless of its retinal eccentricity. Indeed, both central and peripheral visions were equally skilled at using radial and lamellar flow to control posture. Nevertheless, differentiation of optical flow information in its geometrical structure is incomplete when children learn to stand (Stoffregen et al. 1987). The differentiation between modalities also occurs later in childhood.

Position of the flow support

Up to now, the differential effects of the visual flow as a function of the retinal location, for detecting and controlling self-motion, have not been fully assessed (optical flow stimulating either the upper versus lower or the left versus right side of the visual hemifield). Numerous experiments provide vertical surfaces for the flows such as those used on the walls of swinging rooms (Lee and Lishman 1975; Delorme and Martin 1986). On the contrary, the effect of the motion of horizontal textures on postural stability is not yet fully known (Clement et al. 1985), although the ground surface is an essential frame of reference in everyday life. We have previously demonstrated (Flückiger and Baumberger 1988) that adults do react posturally with shorter latencies with a horizontal context than with optical flows projected on vertical supports. The lower visual field (LVF) advantages found for texture flow perception (Levashov and Levashova 1996; Levashova and Levashov 1996) and apparent motion perception (Osaka 1993) are also of converging evidence, which emphasises the putative role of the ground as a reference frame for controlling posture. The LVF superiority reported for texture flow perception (Levashov and Levashova 1996) has an 'ecological' explanation. Indeed, most of the existing objects and obstacles for a walking person are located on a texture ground surface in the LVF.

In contrast to the extensive studies dealing with both of these variables, the differential effects of an approaching (AOF) and a receding optical flow (ROF) have received surprisingly little attention. Indeed if one refers to the most common movements encountered by subjects during their displacements, one observes that during terrestrial locomotion they are mainly exposed to a flow approaching the observer. Therefore, one can advance a hypothesis concerning the role of these two types of visual flows from an ecological perspective (Flückiger and Baumberger 1990). In reference to flows acquired during natural locomotion, one of the main questions that remains is to discover whether an approaching visual scene has a different effect from a receding one (Baumberger et al. 2000). In fact, even though data on this question have been recorded with adult subjects (Lestienne et al. 1977; Woollacott et al. 1988; Bardy et al. 1996) none exists, to our knowledge, for children. Bardy et al. (1996) showed that adaptive control of sway during a walk in a hallway is based on congruent expansion and parallax cues in natural environments. Some authors, comparing a standing subject to an inversed pendulum (Nashner and Berthoz 1978), explain the behavioural asymmetry between backwards and forwards bending with approaching and receding flows by a biomechanical model. We explained the asymmetry of adults' postural readjustments as a function of the flow direction by a possible difference in perceptual processing (Flückiger and Baumberger 1988, 1990).

Effect of optical flow on standing balance in children

It has most often been argued that the role of vision is different according to the subject's age. However, comparisons between different experiments are difficult because age ranges rarely overlap from one author to the other and no consistent developmental model can be inferred from the literature. As an example, authors working with the youngest subjects covered either an age range from 12.5 to 17 months (Butterworth and Hicks 1977), dealt with 2-, 3- and 4-month-old infants (Jouen 1985) or with 3-day-old babies (Jouen 1988). Gibson (1979) has emphasised the importance of optical flow fields, generated from ego-motion, for regulating our self-orientation. Movement of the body generates a global motion of the visual scene across the retina (i.e. an optical flow), which specifies the movement's kinematics properties. In the moving room paradigm, Lee and Lishman (1975) showed that children aged from 13 to 16 months develop a ‘visual proprioceptive control’ of stance according to the number of weeks of their walking experience. An extensive use of these optical devices permitted to show the prevailing role of the peripheral retina and the proprioceptive function of vision in regulating postural sway (Amblard and Carblanc 1980; Delorme and Martin 1986) thus supporting the ‘peripheral dominance’ theory.

Critical sensorimotor developmental periods in the development of standing balance have been recognised by Shumway-Cook and Woollacott (1985) between the 4th and 6th year, whereas 7- to 10-year-old children seem to show almost adult-like responses. This demonstration was based on 5-s records of stability that were sufficient to show postural synergies with EMG but the visual inputs were stationary. This may explain why such an early integration of multimodal inputs was observed. Developmental changes in different components of postural responses have been emphasised between children and adults as a function of the frequency of visual information. Children’s stance control responds both to high and low frequencies whereas adult’s responses match only low frequencies, around or below 0.3 Hz (Gielen et al. 1988). Correlations between sways and a moving room decreased at faster speeds relative to lower speeds (Stoffregen 1986). Postural responses of infants induced by moving room oscillations always occurred at 0.52 Hz in 7- to 48-month-old infants in Delorme et al. (1989), at 0.6 Hz in 5-, 9- and 13-month-old infants in Bai (1993) and at 0.8 Hz in 36- to 64-months-old children in Schmuckler’s (1997) studies (although postural stance differed from one protocol study to another). The gain of amplitude in postural responses was a mixture of adult- and non-adult-like features, whereas timing (or response latency) of responses conformed to those of adults. Both the onset and magnitude of the looming effect was shown to depend on the children’s postural orientation (Bertenthal and Bai 1989).

Appropriate organised postural and muscular responses (to correct the perceived loss of equilibrium induced by the moving room perturbations, where visual cues conflict with postural cues) were found in infants as young as 5 months, i.e. well before they were able to stand up by themselves (Foster et al. 1996). In contrast, other studies have shown that following a translation of the supporting surface (the covariation between visual, vestibular and somatosensory cues contributes to the sense of sway), a distal-to-proximal activation of the body’s posterior muscles (i.e. leg and trunk) was elicited. The activation grew to be similar to those observed in adults as soon as infants (i.e. over 8 months) were able to maintain themselves in a standing position (Woollacott and Sveistrup 1992; Sveistrup and Woollacott 1993, 1996). However, the onset latencies were longer and more variable than those observed in adults subjects.

Interaction vision × new acquisition

From the developmental point of view, it is now generally agreed that new skills for regulating posture are often linked with an increased dependence on visual cues well before the development of a more adult-like and multisensory use of information (Shumway-Cook and Woollacott 1985; Foster et al. 1996). Increasing reliance on visual cues was systematically observed as children (12.5–17 months) learned to sit without support (Butterworth and Hicks 1977) or became able to maintain themselves in a standing position (Lee and Aronson 1974). The same phenomenon was observed at the onset of independent walking (Stoffregen et al. 1987; Foster et al. 1996), and also during each new period of acquisition of segmental stabilisation strategies (Assaiante and Amblard 1993).

Schmuckler and Gibson (1989) found an enhanced reliance to dynamics visual cues in 1- to 3-year-old children, when walking around obstacles in a route-finding situation relative to when no obstacles were present in the child’s path. These results suggest that sensitivity to optical cues and their effective use for regulating balance depend highly on their usefulness and on the relationship that links posture and suprapostural tasks (Stoffregen et al. 2000).

Higgins et al. (1996) showed, with the moving room paradigm, that directionally postural responses to sidewall optical flow occurred mainly in infants with self-produced locomotor experience. Artificial simulation of self-produced locomotor experience was also shown to induce a similar pattern of postural response. Infants without self-produced locomotor experience were confined to a global use of the optical flow. Motor and perceptual experiences were shown to be a key factor influencing the ability to differentiate and use portions of optical flow fields for postural regulation. In adults, peripheral and central vision contributed equally to postural stability for both mediolateral and anteroposterior oscillations, when somatosensory information was not altered (Nougier et al. 1997). Conversely, a differential use of peripheral and central vision occurred during somatosensory perturbations. Indeed, peripheral vision was more efficient in regulating anteroposterior oscillations than for mediolateral oscillations, whereas central vision was as efficient for controlling the centre of foot pressure (CoP) oscillations in both planes. Globally these results support Stoffregen’s (1985) interpretation emphasising the peripheral retina advantage both in adults and children (Stoffregen et al. 1987) when it is stimulated by the lamellar structure of the optical flow elicited by the anteroposterior body movements with respect to the environment. A study by Nougier et al. (1998) emphasised an adult-like pattern of use in children of peripheral and central vision for controlling upright stance. However, a critical developmental period for the use of peripheral vision was observed in their study, where a central advantage in 8-year-old children was found to greatly reduce postural oscillations. Other similar results were reported in the literature. The age of 6–7 years seemed to be a transitional phase in the development of the

Table 1 Details of participants

Age groups	Mean age (years)	Number of subjects	Number of boys	Number of girls	Mean height (cm)
7 years old	7.53 (±3.9 months)	10	4	6	127.8 (±5.12)
8 years old	8.30 (±3.1 months)	12	7	5	133.4 (±4.78)
9 years old	9.49 (±2.8 months)	10	5	5	137.7 (±5.96)
10 years old	10.3 (±2.7 months)	12	6	6	139.9 (±3.34)
11 years old	11.3 (±3 months)	12	5	7	146.9 (±7.38)
Adults	30.18 (±10.01 years)	12	6	6	169.3 (±8.09)

peripheral visual control of locomotor equilibrium (Assaiante and Amblard 1996). Indeed, sensitivity to peripheral optical flow in controlling equilibrium while walking on a beam disappeared transiently in 7-year-old children.

These transition phases also went well with the emergence of new sensorimotor strategy where use of sensory cues seemed to shift from one sense to another. Assaiante and Amblard (1993) found a non-monotonic mastering of head stabilisation strategies in children. A bifurcation was observed around the age of 7 years where an adult-like pattern emerged in sensorimotor coordination, i.e. the head stabilisation of vestibular origin was more frequently used than head-trunk stiffening while children were subjected to difficult balancing tasks and this even in darkness.

Feedback versus feedforward postural control

Various studies evidenced the different duration of feedback maturation compared to feedforward-based control processes subserving compensatory postural activities (Haas et al. 1989). Sudden postural disturbances, as in unpredictable and externally imposed unloading, lead to successive qualitative changes in the form of movement control (Hay and Redon 1999). These two components of postural control improve gradually, but feedforward processes emerge and are mastered later on. The development of feedforward preparation for self-generated perturbations accompanying voluntary movements may not fully be completed by 8 years of age in a stepping task (Stemmons Mercer et al. 1997) and during rise on tiptoe (Haas et al. 1989).

The aim of this research is to study long-term reactions of schoolchildren in an experimental setting generating a unidirectional motion of optical textures directly on each subject's natural walking path. In this kind of visual context it will also be possible to dissociate the postural effects of AOFs and ROFs and hence to assess the developmental course of the posture regulation proprioceptive function of vision. In our device, the AOF is specified by texture expansion within the peripheral array of dots, whereas an ROF is specified by texture contraction resulting visually in an apparent endless vanishing of the dots array out of the field of view. The use of sway response as an indicator of the perception of moving surroundings has led to the following evidence about the influence of vision on postural control.

First, we postulate that with a ground texture the decrease of visual dominance in postural control of stance might occur later in development and consequently the transition phases described in the literature would shift in age. In this perspective, we would agree with Jouen and Lepecq (1990) arguing that postural development would be explained better in terms of intersensory factors rather than as the evolution of a specific modality. New data collected so far with poorly studied schoolchildren could throw some light onto this problem. Second, the progressive increase of schoolchildren's experience with approaching horizontal flows, encountered in autonomous displacements, will determine direction-specific reactions.

The study of the developmental differential effects of an AOF and an ROF on a ground surface could provide insights into the factors contributing to the multisensory control of posture. The aim of this research was to provide a detailed analysis of postural reactions in schoolchildren (7-, 8-, 9-, 10- and 11-year-old) and adults in response to AOFs and ROFs. These ages were chosen because of the critical period frequently reported around the age of 7–8 in the various studies quoted above, investigating both postural and motor development in children. We hypothesised that we would find an adult-like contribution of either approaching or receding flow to postural control at age 10, and a non-monotonic development between the ages of 7 and 11. Based on literature findings, we also expected a critical period where the use of dynamic visual cues, patterned by the ground for regulating posture, should diminish well beyond the age of 7–8 years. The question can be put in another way: when observers receive imposed optical flow while standing, the optical flow produced by self-motion must be distinguished from the optical flow superimposed by the externally moving texture. How are such flow ambiguities solved and from what age can relatively mature adaptations be observed?

Materials and methods

Subjects

Fifty-six children aged from 7 to 11 years and 12 adults, with normal or corrected to normal vision, voluntarily participated in the experiment. All children studied in the same school and had no learning disabilities. The procedures were explained and informed consent was obtained from the parents for the children's participation and from the adults who participated. All participants (see Table 1 for details) were naive as to the purpose of the experiment. Children were divided into five age groups, and their heights were measured before they started the experiment in order to control the resultant apparent change in the texture's spatial frequencies.

Apparatus

The experiment took place in a 3.4×12.5-m laboratory. The entire floor was used as a screen on which a pattern of circular light spots was projected by a texture flow generator (TFG). Large mirrors fixed vertically to the longer lateral walls reflected to infinity the floor surface in front of the subject. The surface of the walls above the mirrors was covered with a black cloth. The motion of the texture along the main axis of the experimental room produced an optical flow in the sagittal axis relative to the subject. The TFG was suspended from the ceiling in the middle of the room. The subject stood at the end of the room, 1 m from the back wall.

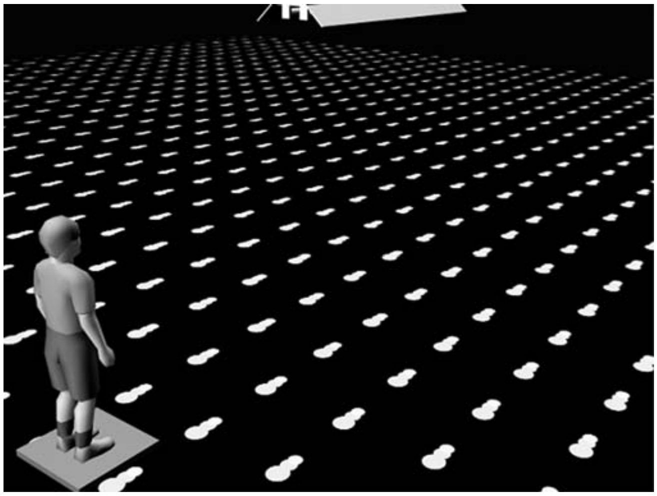

Fig. 1 Illustration of the experimental device. In this example, the subject standing on a force platform was submitted to a forward optical flow. The motion direction of the dots is specified via an artificial drag effect applied to the dots. The optical flow projected on the ground is generated from the texture flow generator fixed to the ceiling. Side mirrors are not visible but they nevertheless contribute to perceiving the ground texture as laterally infinite

Texture pattern

Circular light spots were distributed regularly on the floor (see Fig. 1). The spots had a diameter of 9 cm and were spaced 50 cm apart. When the subject looked at the fixation point (7.5 m away) the ground texture covered 58% of the field view on the vertical meridian. The upper part of the field corresponded to the black cloth surfaces. The mean spatial frequency at 7.5 m ranged from 1.7 to 1.29 cycles/deg according to the actual height of our subjects (129–169 cm). The intensity of the light spots on the ground decreased exponentially from a point in the middle of the room perpendicular to the light source. The texture was set in motion by the TFG. The apparatus as well as the visual scene according to the subject's vantage point are described in Flückiger and Baumberger (1988).

Records of body sway

The postural responses of standing subjects were measured by a unidirectional force platform (5×49×56 cm). Under the platform a force transducer was mobile along the sagittal plane to allow the adjustment of the electric output signal according to the weight of the subject. Each body sway resulted in a translation of the CoP in an anterior-posterior direction. The change of the CoP on a force platform is a good measure of the variation in the position of the centre of gravity when body oscillations are below 1 Hz (Gurfinkel 1973). After being amplified, the analogue transducer output was digitised at 25 Hz with an analogue/digital interface on a PC computer. All data signals were then filtered with a mobile median (on 12 values) from which was subtracted the average values of the reference period (motionless texture) of 24 s (i.e. 600 points at a frequency of 25 Hz). The result was divided by the standard deviation of all signals. Postural responses were then computed in arbitrary units.

Experimental design and procedure

Postural readjustments were recorded by the changes of foot pressure on a force platform during two periods of 92-s exposures. The experimental conditions (see Fig. 2) consisted of 44-s exposures to a moving texture that is either approaching (AOF) or receding (ROF) from the subject. Before (Fix1) and after (Fix2) the optical flows, a 24-s motionless texture served as a reference condition. The subject was first exposed to a motionless texture during 24 s (Fix1), then to an approaching or receding flow during 44 s (AOF1+AOF2, ROF1+ROF2) and finally to another motionless texture during 24 s (Fix2). The order Fix1-AOF1-AOF2-Fix2 and Fix1-ROF1-ROF2-Fix2 was counterbalanced. The experimental design included three factors. The first one was age divided into six age groups. The second, called 'conditions', corresponded to the four uninterrupted periods of postural readjustment record (Fix1-Mv1-Mv2-Fix2). This factor included the initial (Fix1) and final (Fix2) exposures (24 s) to the motionless texture as well as two uninterrupted periods (Mv1 and Mv2 corresponding to respectively AOF1-AOF2 and ROF1-ROF2) of 22 s during which an optical flow was presented. Finally the factor called texture 'direction' had two levels including an approaching (AOF) and a receding flow (ROF).

The texture velocity in the flow presentation conditions was 1.4 m/s (about 5.0 km/h) corresponding approximately to a natural walking speed for adults and a fast walking speed for our younger children.

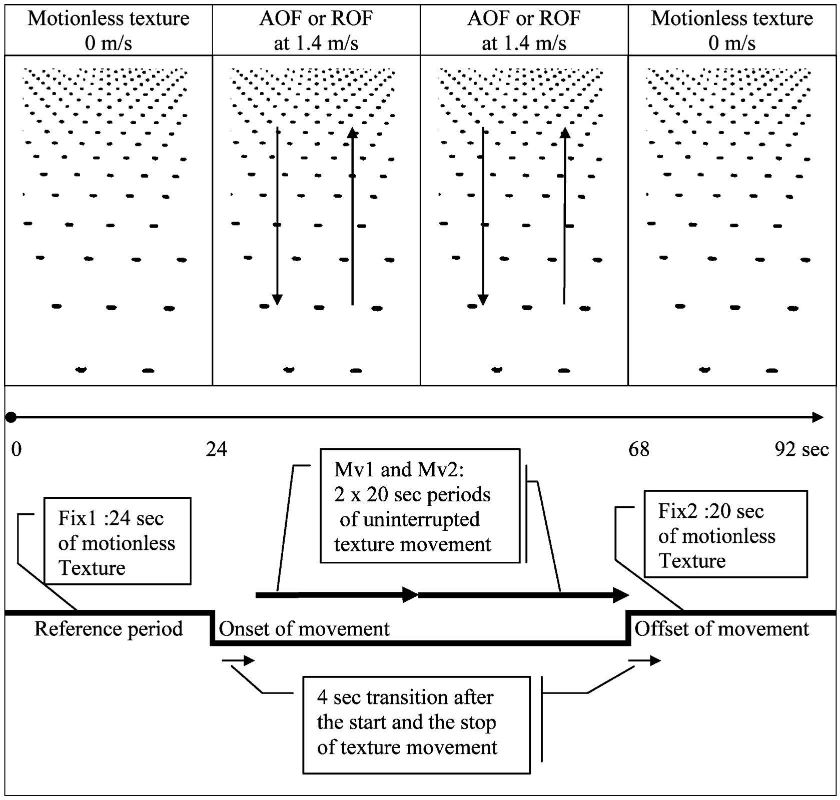

Fig. 2 Illustration of the experimental design. At the beginning (*left part of the figure*) the texture is motionless (*Fix1*) during 24 s. After that the texture moves (*middle part*) in an approaching or receding direction (*AOF* or *ROF*) during uninterrupted periods (*Mv1* +*Mv2*) of 44 s (4 s transition +2×20 s of motion=44 s) followed by a second motionless texture (*Fix2*) during 24 s (4 s transition+20 s=24 s). The *top view* illustrates the texture perspective and the experimental conditions. The *bottom view* shows from *left* to the *right* the time progression and the description of each part of the 92-s period

Subjects stood barefoot on the force platform with their feet together (normal Romberg). They were instructed to stand relaxed in an upright posture keeping optimal balance with their arms along their sides and to look straight ahead in an area where a fixation point was flashed at the beginning of each experimental condition (7.5 m). The platform output was calibrated and subjects were told that at the end of the experiment they would be asked to describe the motion they had perceived. No feedback was given during the experience but children were praised periodically for their good effort (for example, ‘that’s great’ or ‘you’re doing a good job’).

Analysis of data

Computation of sway latencies

A first indication about the subject’s sensitivity to an optical flow projected on the ground surface was obtained by the computation of sway latencies. The criterion adopted for determining the initial postural response at each transition between conditions was 63% of sway with respect to the maximal CoP displacement seen in the preceding condition (Lestienne et al. 1977; Flückiger and Baumberger 1988). The purpose of this first analysis was to assess the effects of the optical motion Onset versus Offset as a function of flow direction (AOF versus ROF) on the postural sway latencies across the six age groups (7, 8, 9, 10 and 11 years and adults). Nine subjects without a clear displacement of the CoP at the Onset and Offset of the texture motion were removed from the analysis. Statistical analyses were performed on all data with missing values (restricted to SL only) matching nine subjects withdrawn from the analysis (children aged 7 years: n=3; 8 years: n=0; 9 years: n=2; 10 years: n=1; 11 years: n=1; and adults: n=2). Computation of postural latencies at onset motion was obtained by measuring the time elapsed between the onset of motion period 1 (Mv1) and the first postural response observed. Postural latencies at offset motion were obtained by measuring the time elapsed between the offset of motion period 2 (Mv2 and thus the onset of the motionless period 2, Fix2) and the first postural response observed. The postural latencies statistical design will consist of performing a 6 Ages×2 Motion (onset versus offset)×2 Directions of motion (AOF versus ROF) analysis of variance (ANOVA).

Analysis of the postural orientation

The second computation of the individual records of body sway was an analysis of the entire raw data series sampled at 25 Hz. In order to suppress transition effects, the data were subsequently condensed into 20-s intervals (at the beginning and at the onset and offset of texture movement we suppressed the first 4 s); for each interval a mean value of foot pressure (CoP) was computed which resulted in a total average postural orientation for each condition. The postural orientation represents roughly the new position of the body mass (inferred from foot pressure changes) that a subject adopts in an experimental condition. According to the experimental design the data were analysed using a multivariate analysis of variance: Age (6)×Conditions (4)×Directions (2) factorial design ANOVA.

Analysis of the postural stability

The CoP recordings were also submitted to a spectral analysis. As for postural orientation, we reduced the analysis to 20.48 s duration for all conditions thus eliminating transitory sways which occurred within 4 s of the onsets and offsets of the texture motion. For each condition, the power spectrum of the component frequencies of the CoP was obtained by means of a standard fast Fourier transformation program (FFT; to calculate FFT we used a number of points corresponding to a power of two: 2^{10}=512 pts at 25 Hz⇒20.48 s for each condition Fix1, Mv1, Mv2 and Fix2). The postural stability was calculated from the logarithm of the power spectrum between 0 and 2.5 Hz (25 Hz/512 pts=0.048-Hz bins) (Isableu et al. 1997). A decrease in this averaged mean power spectrum expressed an increase in postural stability.

This classic approach to the analysis of oscillatory behaviour consists of a transformation of the time-series record into the frequency domain. This allows the identification of specific frequencies of oscillation, as well as their relative power and phase. The overall measure of a subject's (CoP) postural stability was thus introduced in an appropriate ANOVA, in order to make comparisons between experimental situations and groups, which constituted the independent variables. The influences of age, body height and body mass on sway parameters were also assessed.

Verbal report

Finally we collected verbal responses of the subjects about their self-motion perception in the optical flow. After the experimental session they were asked: 'Did you feel that your body was sometimes displaced through the room during the projection of the mobile texture patterns?'

Results

Computation of sway latencies

A first indication about the subject's sensitivity to an optical flow projected on the ground surface was obtained by the computation of *sway latencies* (SLs). Two aspects of this indicator were relevant in our perspective. The first one concerns the range of these values compared to previous experiments using other supports than the ground for the optical flow. In that respect the present data showed a latency range between 1.4 to 3.4 s at the onset and between 1.7 to 3.3 s at the offset of the moving texture as a function of flow direction (AOF and ROF, respectively). Overall, these SL values in response to the motion offset

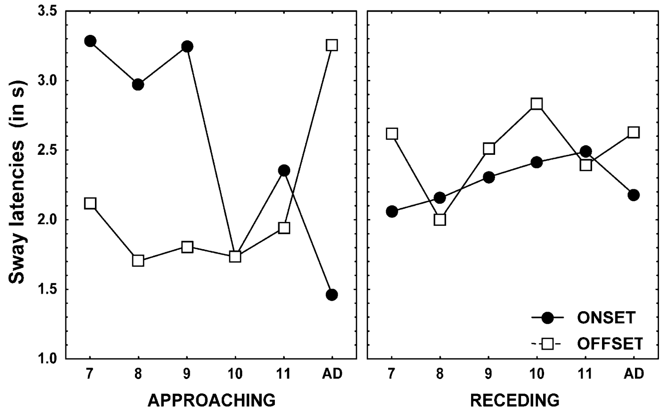

Fig. 3 Mean sway latencies interaction between onset and offset motion as a function of age in each direction of optical flow. *AD* Adult

of the texture were much shorter than the average of 5.2 s obtained by the same means of computation by Lestienne et al. (1977). The second important aspect of SL concerns its evolution as a function of age (see Fig. 3).

A 6 Ages×2 Motion (onset versus offset)×2 Directions of motion (AOF versus ROF) ANOVA showed that main effects of age ($F_{(5,46)}$=0.42), directions ($F_{(1,46)}$=0.28) and motion onset/offset ($F_{(1,46)}$=0.24) were not significant. The significant interaction of Motion onset/offset×flow Direction ($F_{(1,46)}$=4.65, P<0.04) showed that approaching flow induced significantly shorter SL at the offset than at the onset of the motion. Significant differences were also found in SL between AOF and ROF flows at the motion offset only ($F_{(1,46)}$=5.07, P<0.03).

Effects of both onset and offset of the approaching optical motion induced significant changes on postural SL with age (Age×Direction, $F_{(1,46)}$=7.41, P<0.01 and Age×Motion, $F_{(1,46)}$=12.02, P<0.001; linear model). Second, effect of motion onset with age varied with motion direction and led to differential SL responses whereas effect of motion offset did not (Age×Directions×Motion, $F_{(1,46)}$=8.98, P<0.004).

Effects of *motion onset of an AOF flow* (ranged between 3.3 s in 7-year-olds and 1.4 s in adults) on postural latencies linearly and significantly decreased with age ($F_{(1,46)}$=7.85, P<0.007). *Post hoc* analyses (Duncan methods, P<0.05) showed that children between 7 and 9 years old clearly reacted with longer latencies at the motion onset than adults.

Conversely, the effect of the *motion offset of an AOF flow* on postural latencies (ranged between 2.1 s in 7-year-olds and 3.3 s in adults) increased linearly and significantly with age ($F_{(1,46)}$=3.92, P<0.05). *Post hoc* analyses showed that children between 7 and 11 years old reacted with shorter latencies at motion offset than adults. Finally, postural sways latencies induced by the onset or the offset motion of an AOF differed as a function of age (see Fig. 3). SLs at motion onset and SLs at motion offset were significantly different in the 7-, 8- and 9-year-old children, did not differ in 10- to 11-year-old children and became different in adults (in the opposite direction compared to children). Indeed, children between 7 and 9 years old clearly exhibited shorter latencies at motion offset than at onset. Conversely, adults reacted with shorter latencies at motion onset than at motion offset.

Overall, these results showed that SLs evolved with age and that they were differentially affected both by the onset and by the offset of the motion texture and mainly in response to an AOF. SLs were found to decrease with age at the motion onset and to increase with age in response to the motion offset of an approaching optical texture. Shorter SLs at onset and longer at offset of an approaching motion were found in adults. Onset of an AOF motion likely induces the most disturbing effects on postural control, so adults respond with a shorter SL that was not observed in children. Interestingly, results also showed a critical age period of neglect, between 10 and 11 years old, to both onset and offset of an AOF motion. In the ROF, data showed that both onset and offset motion induced significant change in SL duration but independently of age.

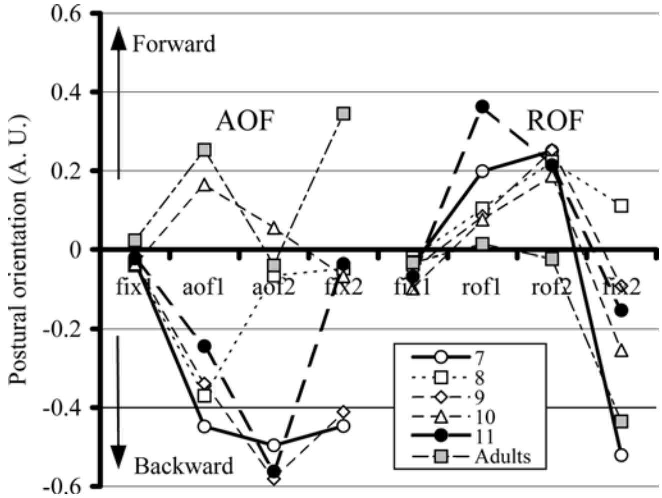

Fig. 4 Mean postural orientation (PO shift of the centre of foot pressure in arbitrary units; *A.U.*) as a function of age, direction of motion and experimental condition (AOF: Fix1-aof1-aof2-Fix2 or ROF: Fix1-rof1-rof2-Fix2 of 20 s each)

Evolution of postural orientation

The second set of data concerns the evolution of the *postural orientation* (PO) corresponding to the mean position of the body mass during each experimental condition. The orientation was measured by the change in the centre of pressure (CoP).

We had to establish first whether, with an optical flow, subjects did change the position of their centre of pressure and then, whether the shift of PO was specific to the direction of the optical flow.

We decided to study in more detail the specific impacts of directional effects of the optical flow at onset and offset motion, separately, as a function of the age groups. Effects of the motion onset on PO were assessed by comparing the average PO in the motionless texture (i.e. Fix1) with the average PO measured in the first period of motion texture (Mv1). Effects of the motion offset was assessed by comparing the second period of motion texture (Mv2) with the following motionless texture (i.e. Fix2).

Effect of motion onset on postural orientation

Postural orientation responses of the CoP (see Fig. 4) to optical motion onset were submitted to a 6 Ages×2 Texture conditions (Fix1 versus Mv1) for motion Onset×2 Direction of motion (AOF versus ROF) analysis of variance (ANOVA). Results showed a significant main effect of Direction ($F_{(1,62)}$=5.93, P<0.018). Main effects of Age and motion Onset (Fix1 versus Mv1) were not significant. The ANOVA showed significant two-way interactions of Direction×motion Onset (Fix1 versus Mv1; $F_{(1,62)}$=5.71, P<0.02), Age×Direction ($F_{(5,62)}$=2.76, P<0.03) and a significant three-way interaction of Age×Direction×motion Onset ($F_{(5,62)}$=2.77, P<0.02). Thus, the canonical PO responses expected were observed, i.e. directionally tuned with the Direction of motion. PO was significantly shifted backwards in an AOF ($F_{(1,62)}$=6.48, P<0.01; Mv1 and Mv2 pooled together), whereas it was shifted forwards in the ROF (quasi-significant; $F_{(1,62)}$=3.80, P=0.055; with Mv1 and Mv2 pooled together). Otherwise, effects of motion onset in an AOF decreased with age (i.e. the backward lean decreased with age; $F_{(1,62)}$=8.93, P<0.004), whereas effects were minor and almost constant throughout age in the ROF. In the 8- and 10-year-old children and adults, PO was not affected by motion onset whatever the direction, whereas it was in the 7-, 9- and 11-year-old children (AOF flux mainly). Indeed, 7- and 9-year-old children were significantly pushed backwards at the motion onset of the AOF texture ($F_{(1,62)}$=6.85, P<0.01) and ($F_{(1,62)}$=3.81, P<0.05), respectively, whereas PO responses were reversed in adults (quasi-significant, $F_{(1,62)}$=3.77, P<0.057). Onset of the receding flow almost did not cause any significant changes in PO whatever the age considered.

Effect of motion offset on postural orientation

Main effects of Age ($F_{(5,62)}$=0.94, P<0.46) and Direction were not significant ($F_{(1,62)}$=0.48, P<0.49). Results showed a significant main effect of the motion offset to PO ($F_{(1,62)}$=7.26, P<0.01 and Direction×motion Offset ($F_{(1,62)}$=32.03, P<0.001), indicating a canonical after-effect displacement of the PO in the motionless texture condition. Effects of motion offset on PO responses were significant in an ROF ($F_{(1,62)}$=23.47, P<0.001) and in an AOF ($F_{(1,62)}$=7.05, P<0.01), inducing opposite effects to PO. The backward displacement of the PO induced by the onset of an AOF was, indeed, cancelled at its offset by a forward displacement, whereas the PO (displaced forwards with the ROF onset) was displaced backwards at the ROF offset and resulted in a persistent backward lean of the subject's vertical posture in the motionless period (Fix2), whatever the age. ROF offset induced stronger PO shift than AOF offset motion ($P<0.05$).

The main effect of Age did not interact either with motion Direction ($F_{(5,62)}=1.21$, $P<0.31$) or with motion Offset ($F_{(5,62)}=0.94$, $P<0.46$) or with Direction×motion Offset ($F_{(5,62)}=0.82$, $P<0.54$). A trend can be signalled about the two-way interaction of Age×motion Offset (with a linear model contrast): effect of motion Offset tended to decrease linearly with increasing age ($F_{(1,62)}=3.43$, $P<0.07$) independently of the motion direction.

To summarise, for all subjects, the visual control of PO was directionally tuned, but also varied with the onset or offset of the optical flow. Canonical PO responses (i.e. a backward postural lean at onset motion in an AOF and a forward lean in an ROF, whereas those effects were reversed at motion offset) were indeed found but mainly in response to an AOF in all groups of subjects, except in 8- and 10-year-old children which were found to be not very affected whatever the direction of motion. They showed the smallest change in their starting point of equilibrium. In adults, effects of AOF motion were found to shift their PO in the opposite direction of the optical flow (i.e. leaned forward), contrasting with the canonical pattern of responses observed in the youngest children (leaned backward when influenced). This last outcome found in adults also contrasts with results in the literature. Interestingly, the pattern of PO responses at motion onset found in the 10-year-old children, albeit not significant, was directed like the adults (and reversed compared to the youngest children). This age seems to suggest the existence of a critical transition period in the development of PO control. Eleven-years-olds showed that this mastering took some time. Eight-years-olds showed a kind of ‘transient neglect’ (like 10-years-old) with respect to visual flow, whatever its direction, but perhaps for others reasons, which will be tackled in the Discussion.

Moreover, results have shown that effects of motion texture on PO decreased linearly with age and more particularly in an AOF. On the other hand, effects of motion offset on PO in response to AOF and ROF showed only a marginal statistical decreasing after-effect on PO with age. Taken together, these results showed that, at motion offset, PO displacements appeared in the opposite direction to that of optical flow direction. These canonical responses confirmed expected behaviours on PO.

Instability produced by the optical flows

The third computation of postural responses concerns the instability produced by the optical flows. The overall measure of a subject’s *postural stability* (PS) was calculated (see Analysis of data) for each condition (i.e. Fix1, MOV1, MOV2, Fix2). A rise in the PS value expressed an increase instability. The results are shown in Fig. 5.

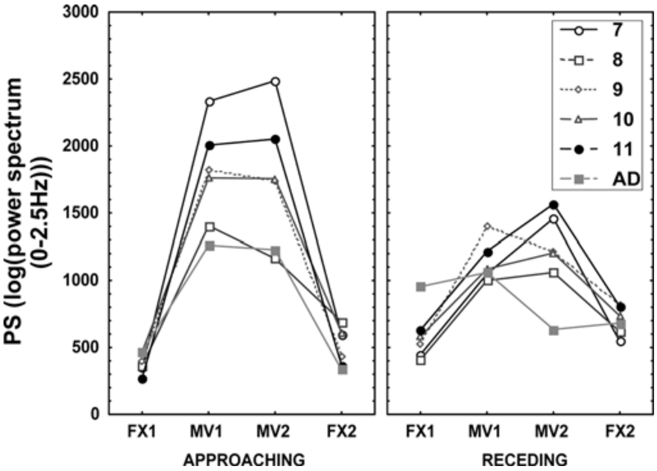

Fig. 5 Postural stability (calculated with a Fast Fourier transformation) as a function of age and experimental condition

Effect of motion onset on postural stability

The results showed that main effects of motion Onset (Fix1 versus Mv1) ($F_{(1,62)}=141.48$, $P<0.001$) and motion Direction (AOF versus ROF) ($F_{(1,62)}=7.07$, $P<0.01$) on PS were significant. The main effect of Age did not reach the significance level ($F_{(5,62)}=1.25$). The interaction of motion Onset×Direction ($F_{(1,62)}=26.49$, $P<0.001$) was significant. The decomposition of this interaction into its main effects showed that motion onset was significant in AOF ($F_{(1,62)}=135.61$, $P<0.001$) as well as in an ROF motion ($F_{(1,62)}=25.35$, $P<0.001$), but that effects of an AOF were significantly more destabilising than those of an ROF ($F_{(1,62)}=20.83$, $P<0.001$). Moreover, the destabilising effect of motion onset on balance also differed with age ($F_{(5,62)}=2.50$, $P<0.04$) and a more detailed analysis revealed that these effects seemed to decrease linearly with age (i.e. with a linear polynomial contrast; $F_{(1,62)}=4.40$, $P<0.04$) and mainly in an AOF motion texture ($F_{(1,62)}=7.38$, $P<0.01$), although some age groups (8- and 11-year-old children) deviated from this linear trend (see Fig. 5).

Effect of motion offset on postural stability

The aim of this last analysis was to assess the magnitude of the after-effect induced by the motion period (i.e. the residual effect of motion after its offset on PS in the motionless period) on PS, as a function of the flow direction and age.

The main effect of motion Offset (Mv2 period versus Fix2) ($F_{(1,62)}=104.06$, $P<0.001$), motion Direction (AOF versus ROF) ($F_{(1,62)}=4.29$, $P<0.04$) and Age ($F_{(5,62)}=3.65$, $P<0.006$) to PS were significant. The motion Offset×Direction ($F_{(1,62)}=19.77$, $P<0.001$) interaction was significant, indicating that subjects were always more destabilised by the motion offset in an AOF than by the ROF. The effect of motion offset also differed with age ($F_{(5,62)}=3.68$, $P<0.005$). This interaction between both factors fits better onto a cubic model ($F_{(1,62)}$=13.70, P<0.001) than a linear one ($F_{(1,62)}$=2.15, P<0.15), suggesting discontinuous effects of motion offset as a function of age. Indeed, stability values of the 8- and 11-year-olds deviates strongly from the other age groups. This Age×Offset interaction was found to be significant (with a cubic model contrast) in the AOF ($F_{(1,62)}$=7.71, P<0.007) and in the ROF ($F_{(1,62)}$=4.91, P<0.04; with a linear model contrast).

Postural stability in the second motionless period (Fix2), compared to the PS in the initial motionless period (Fix1), was found to be significantly impaired ($F_{(1,62)}$=4.81, P<0.03). Indeed, subjects in Fix2 were found to be less stable compared to their initial performances observed in Fix1. Thus a motion after-effect is present, since subjects did not return to their initial stability performance in the second motionless period. Moreover, this after-effect, present in the youngest children, significantly decreased with age ($F_{(1,62)}$=4.51, P<0.04) to become non-significant in adult subjects. This suggests that the capability to return quickly to optimal equilibrium (Fix1) after visual motion stimuli continuously matures until adulthood.

Optical flow was shown to induce destabilising effects on postural balancing, the magnitude of which mainly depends on motion direction. Motion onset and offset were both found to be equally destabilising. The ROF was found to be less destabilising than the AOF and these differences were more pronounced with age at motion offset. The reliance on dynamics cues was shown to decrease with age mainly at motion onset of an AOF and at offset of an ROF. Eight-year-olds were found to be as stable as adult subjects and not very affected by optical flows.

Correlational analyses

The relationships between SL, PO and PS as indicators of linear vection were studied during child development (SL data of all age subjects were plotted against PO and PS; and PO versus PS).

Postural stability seemed to improve (i.e. subjects were more stable) with age at onset of an AOF with an increasing forward shift of the CoP (r=−0.24, P<0.05) and this result was also found to be significant in the 20- to 40-s period (r=−0.28, P<0.02). Interestingly, the adult subjects were found to adopt inclination responses in the opposite direction to the AOF direction at onset (in the first 20 s of optical motion), presenting an inverse pattern of responses compared to children. Thus, the forward inclination strategy could be seen as an interesting solution reducing the effect of the AOF motion and thus keeping optimal postural balance. This outcome takes an adaptive significance since SLs were found to be significantly shorter at the motion onset of an AOF [correlated both with the improvement in PS (r=0.32, P<0.02) and when subjects increasingly leaned backward (r=−0.30, P<0.03)] indicating some functional motosomesthesic adaptations that matured with age.

Sways latencies were also found to decrease with the improvement in PS at motion onset of an ROF (r=0.32, P<0.01). The more subjects are stable, the shorter are the SLs. The reverse pattern was found at motion offset in ROF, where increasing SLs (r=−0.26, P<0.03) were linked with improving PS. SLs were found to become significantly longer with increasing forward lean in response to motion offset of an AOF texture (r=−0.27, P<0.03). Conversely, a pattern in the opposite direction was found at motion onset of an ROF texture (r=0.36, P<0.01), meaning that SLs became shorter with increasing backward lean. At offset motion of an ROF texture, SLs became longer with increasing backward lean (r=−0.28, P<0.03).

Verbal report

Children and adults were asked how they perceived the optical flow at the end of the experiment. The answers show that more than 90% of the 7-year-old children experienced linear vection (i.e. the subjective sensation of self-motion). This percentage decreased regularly to 55% for adult subjects.

Discussion

The aim of this study was twofold. The first question addressed in this research concerned the development of the visual control of posture. More specifically we investigated whether there are developmental changes in the integration of the directional effects of dynamic visual cues (provided by a ground texture reference) to the development of stance. Specifically, we examined the effects of AOFs and ROFs on the magnitude of postural latencies and the orientation and stabilisation of postural responses.

The main results that emerge from this experiment show that postural responses are directionally specific to optical flow pattern and that they vary as a function of the motion onset and offset. Onset of an approaching flow induced postural instability, canonical shifts in postural orientation and long latencies in children which were stronger than in the receding ones. This pattern of response evolved with age towards an improvement in stability performances and shorter sway latencies. The backward decreasing shift of the CoP in children evolved in adults towards forward postural tilt, i.e. in the opposite direction of the texture's motion. Offset of an AOF motion induced very short sway latencies in children and strong postural instability, but weaker shift of orientation compared to the receding one. Postural stability improved and orientation shift evolved to forward inclinations with age. Sway latencies remained almost constant across age at both onset and offset of the receding flow. Critical developmental periods seem to occur by the age of 8 and 10 years, as suggested by the transient 'neglect' of the children to optical flows. We shall demonstrate that this pattern of response in both children and adults subjects illustrates different levels of maturity in postural coupling with optical flows.

Our first question concerned the specificity of postural orientation as a function of the direction of the optical flow and the age of the subjects. The average postural orientation indicated a consistent response to the optical flow that changes with age. AOFs and ROFs induced opposite orientation behaviours, more pronounced in the AOF. Globally, our results showed that canonical responses occurred in children in response to motion onset and motion offset, and this in both directions of motion texture. In our experiment, 7-, 9- and 11-year-old children exhibited canonical responses of large amplitude (at onset and offset) in both directions (in both AOF and ROF) of the optical flow. On the other hand, 8- and 10-year-old children did not show canonical responses in the direction of an AOF (at both onset and offset), although they appear at the offset of the receding flow only. The backward shift induced by the AOF motion decreased with age. Adult subjects leaned in the opposite direction of the flow.

These results contrast with literature data and suggest a progressively decreasing effect of an AOF motion to postural orientation, reaching its minor value in adult subjects, due to a better integration of dynamic cues. AOF motion induces stronger effects on postural control, because it matches motions that are encountered most of the time in the regulation of most of our daily motor activities. Recent findings (Atchley and Andersen 1998) showed that the processing of visual dynamic aspects is still improving until 14–15 years of age. These results suggest that children are particularly reliant on vision for regulating balance, because they pay less attention to proprioceptive cues than adults. Brandt et al. (1976) showed that the visually induced reorientation of the body towards the direction of a large visual display rotating around the stationary subject's line of sight was predominant in the 2- to 5-year-olds (who are going to fall sometimes) and slowly decreases between 5 and 15 years of age.

Based on the FFT analyses, postural stability develops from schoolchildren to adults. The age of 10 also seems to be a critical point in the development of the visual control of stability in an optical flow. Children of that age may have a more transferable experience with common approaching texture flows.

The second question concerned the role of the ground on the subjects' sensitivity to a moving texture. The most adequate indicator of such sensitivity is the delay in postural response. As sway latencies were not measured in the numerous experiments using swinging rooms (Lee and Lishman 1975; Stoffregen et al. 1987) the only available comparison was research using optical tunnel devices (Lestienne et al. 1977). In an earlier experiment with adults (Flückiger and Baumberger 1988), we showed that sway latencies with a TFG were considerably shorter than with other devices (Lestienne et al. 1977). The present results showed that children react posturally almost two times slower than adults do, at onset of an AOF and that sway latencies decreased with age. These results argue in favour of a multimodal sensory control of posture where the integration of dynamic visual cues provided by the ground frame of reference depends on the maturation of the sensory motor system and/or the evolution in the ability to use them. However, the inverse pattern emerged at the onset of an AOF. Indeed, children react posturally almost two times faster than adults do. These findings suggest functional reliance on somatosensory cues in children. We can therefore assume that the observed postural readjustments were determined by a linear vection effect. This is corroborated by the fact that a higher percentage of younger subjects report an apparent ego-motion in comparison to adults.

The ground seems to be used, in adult subjects, as a fully integrated frame of reference from which postural coordination can be organised. The use of this spatial frame of reference seems to be continuously under maturation from some critical period (8 and 10 years of age) until adulthood, suggesting that the exact adult-like pattern of responses is not fully achieved in children. The pattern of response that emerges in adult subjects is striking since it contrasts strongly with the literature data. The functional specificity of the ground frame of reference is important, compared to other environmental frames of reference analysed in the literature (frontal and side-wall stimulation with the moving room and tunnel devices).

We think that the anti-canonical postural responses observed in adult subjects that emerge in the 10-year-old children must be attributed to functional and adaptive postural responses. These directional responses were shown to be associated with postural balance improvements and shorter sway latencies. We propose to explain this behaviour by a sensorimotor strategy aimed at increasing the weight of somatosensory and proprioceptive information in order to resist the disorienting and destabilising effects of optical flow or to minimise them in any case. This sensorimotor strategy would allow control of the body mass distribution by controlling the differential pressures acting on the different parts of the shoe sole (the sole is wider towards the toes than towards the heels). Indeed, recent findings have shown that cutaneous afferent messages from the main supporting zones of the feet have sufficient spatial relevance to inform the CNS about the body's position with respect to the vertical frame of reference and consequently induces adapted regulative postural responses (Kavounoudias et al. 1998, 2001). Kavounoudias et al. (1999) proposed that proprioceptive information from ankle and neck muscles may be used to control balance and body orientation, with central integration of both tasks. The muscle-spindle inputs would form a 'proprioceptive chain' that functionally links the eye muscles to the foot muscles. The backward postural tilt associated with larger postural instability and longer latencies in children seems to consolidate the idea mentioned beforehand. In this postural orientation, the 'proprioceptive chain' is relaxed and the body mass distributed more towards the heels, which consequently diminishes the efficiency of the muscular reactions of compensation. Children react quickly at the offset of optical flow (AOF) and we claim that this is partly due to the fact that they approach the limits of stability, which consequently increases the likelihood of falling. This postural reorientation might also be due to something else, such as a simple biomechanical effect. Usui et al. (1995) have reported that the foot's centre of gravity in children standing upright shifted towards the toes with increasing age: its distance from the heel was about 36% of the foot length for 3- to 5-year-olds and 42% at 11 years of age.

Our results might also suggest an inability or difficulty in children to switch from an unreliable to a reliable source of perceptual information or an inability to modulate the responses produced following the optical flow perturbations. With increasing age and experience, the ability to solve the conflict improved, with adult subjects demonstrating little sway response. Prokop et al. (1997) had instructed adult subjects to keep their walking velocity (WV) constant, while walking on a self-driven treadmill in an optical flow. They showed that the effect of the relative optical flow diminished by about 45% over the entire walking distance, suggesting that a shift from visual- to leg-proprioceptive control takes place, promoting adaptation over the entire walking distance. For Forssberg and Nashner (1982), postural control depends mainly on the somatosensory inputs, and vision dominates only in situations of intersensory conflicts that children less than 7 years old cannot solve. Assaiante and Amblard (1996) suggest in their ontogenetic model that vision dominates at the onset of each critical period in which new sensorimotor acquisitions emerge, leading to a higher level of postural control. Berthenthal (1996) postulates that the prevailing role of a given sensory input is context-dependent but is not registered in the postural system. Nougier et al. (1997) showed that postural adaptations are both time- and sensory-dependent. The authors suggest that sensory disturbances required subjects to redefine the respective contribution of each sensory input for orienting and stabilising posture. This reweighing mechanism needs time during the trial. Impoverished but also enriched visual and/or proprioceptive information entail transient postural instability. Thus, when sensory systems work within their operating limits (sensitivity threshold and temporal characteristics) a postural adaptation can be observed. This adaptation can be delayed or absent when the sensory inputs are stressed.

One can also suggest that dynamic visual cues patterned by the ground frame of reference imitate translational postural movements in the sagittal plane during walking. However, it may be noted that the rotational movement's components due to bending or tilting axial synergies (bounce and sway) were removed. Thus, retinal extero-proprioceptive flow produced by our oscillatory postural movements was mixed with the rectilinear artificial optical flows generated by our device (TFG). The ambiguity of the visual cues in our experiment can be solved only while resorting to other sensory inputs. Indeed, the improvement in postural balance due to visual flow could be linked with the maturation of cortical reciprocal inhibitory mechanisms allowing the subject to fight against sensory conflicts (Brandt 1999; Brandt et al. 2002; Deutschlaender et al. 2002), reweighing available sensory cues as a function of the physical constraints acting on the subject. It would be obviously logical that such inhibitory mechanisms need time and experience in order to reach satisfactory states of maturity. Converging evidence arises from some developmental studies investigating the contribution of vestibular and somatosensory systems. In these studies (Woollacott et al. 1987; Ashmead and McCarty 1991), infants performed better when vision was unavailable, suggesting an important contribution from somatosensory and vestibular inputs in children's postural development. Barela et al. (1999) also showed that infants use surface contact for mechanical purposes and later for orientation information that affords prospective control of posture. The authors conclude that the calibration exerted by vision on proprioceptive and vestibular systems is still a matter of maturation because mechanical-somatic control is still improving.

Finally, it might be also added that, due to their height, children experienced a stronger rate of visual expansion than adults did. This argument might explain the sensorimotor differences observed between children and adults for AOF. In research on distance estimation (Baumberger and Flückiger 2004) with this same device (TFG), we showed that the differences in performance between children and adults could not be explained by a difference in eye-height. However, the smaller differential postural responses between age groups in the motion receding flow condition cannot uphold this argument.

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